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Review

Bioclimatic Architecture Strategies in Denmark: A Review of Current and Future Directions

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Abstract: Due to climate change, the rise in global temperature causes an increased need for cooling to satisfy occupants' thermal comfort. Application of architecture passive design strategies, so-called bioclimatic architecture strategies, based on the local climate to forego active cooling measures to decrease the conventional heating need and ensure thermal comfort are, thus, becoming highly relevant and vitally important. In an effort to adapt and promote passive architecture design strategies in the new design or renovation of building projects, this literature review fills the gap by identifying suitable bioclimatic architecture strategies in the Danish setting. The literature review adopts the PRISMA flowchart (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), and the outcome is supplemented by screening 25 actual bioclimatic architecture-based building design projects in Denmark. The study shows that a wide range of passive strategies are being researched and practiced in Denmark, whereby the focus for passive heating strategies lies on solar gains, thermal insulation and thermal mass. Among passive cooling strategies, natural ventilation and solar shading are the main strategies investigated. Based on the analysis, it is expected that the use and research of those measures will continue, whereby the passive cooling measures will be of particular future interest in light of increasing outdoor temperatures.

Keywords: climate change; bioclimatic architecture; Danish passive architecture; passive cooling; passive heating

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1. Introduction

European and Nordic countries' average temperatures have been rising since the pre-industrial period and are predicted to increase even further [1,2]. Thus, the period between 2015 and 2020 is considered the warmest since 1850, and the year 2020 was one of the three warmest years recorded so far [3]. The increase in annual average temperature decreases the heating demand for buildings, notably during winters [4,5]. However, rising average temperatures and more frequent heatwaves and nights above 20 °C will also heighten the need for cooling to satisfy occupants' thermal comfort [2,4–6]. The resulting increased cooling energy is at odds with the EU's current efforts to achieve climate neutrality. The need for measures to counteract these climate effects is therefore evident. Climate effects may be counteracted by bioclimatic architecture (see Section 2 for definition). Recent research has shown that bioclimatic architecture, with its application of passive measures, can be an efficient cooling strategy and may reduce the conventional heating need in winter periods [7–9]. In Denmark, passive heating measures have been applied in the design new buildings. They successfully reduced the demand for heating energy; however, they led to increased overheating, notably in the summer [10].

While bioclimatic architecture harbours much potential, suitable bioclimatic architectural strategies at the country level have so far not been formulated [8] for Denmark. This paper fills this gap by reviewing current passive heating strategies in Denmark and discusses the suitability of those measures for future building design. Added to this, the outcome of the literature study is supplemented by screening 25 bioclimatic architecture-based building design projects in Denmark in order also to provide insight into the actual application of the identified strategies in the current practice of building design in Denmark.

In doing so, the bioclimatic architecture is primarily defined towards identifying the passive heating and cooling strategies. Next, search keywords for each passive strategy are specified and used to conduct the systematic literature study. Then, the bioclimatic strategies applied in the 25 actual building projects are characterized and examined, and ultimately the results are presented and discussed.

2. Definition and Identification of Keywords for Literature Search and Characterisation of Passive Design Strategies

Bioclimatic architecture or bioclimatic design is a frequently used but not uniformly defined term. Various definitions with foci on local climate [11], improvement of energy efficiency [9] and thermal comfort [7] exist.

For this study, bioclimatic architecture is defined as follows:

Bioclimatic architecture is the design of a building adapted to the local climate using passive strategies to achieve a favourable indoor environmental quality at the lowest possible energy consumption.

According to Košir [12], two approaches within bioclimatic architecture are analytical bioclimatic design and symptomatic bioclimatic design. The first one analyses the local climate, identifies the bioclimatic potential and determines suitable bioclimatic measures. The latter one analyses vernacular buildings that have already adapted bioclimatic measures and replicates the identified measures [12]. This paper does not distinguish between the architectural strategies emerging from either of the two approaches.

In a bioclimatic context, strategies may involve passive heating, i.e., heat retention and heat admission, and passive cooling, i.e., heat exclusion and heat dissipation. An overview of the passive cooling and heating strategies is given in Figure 1. In the following, the passive strategies are outlined, and keywords for subsequent literature searches are derived.

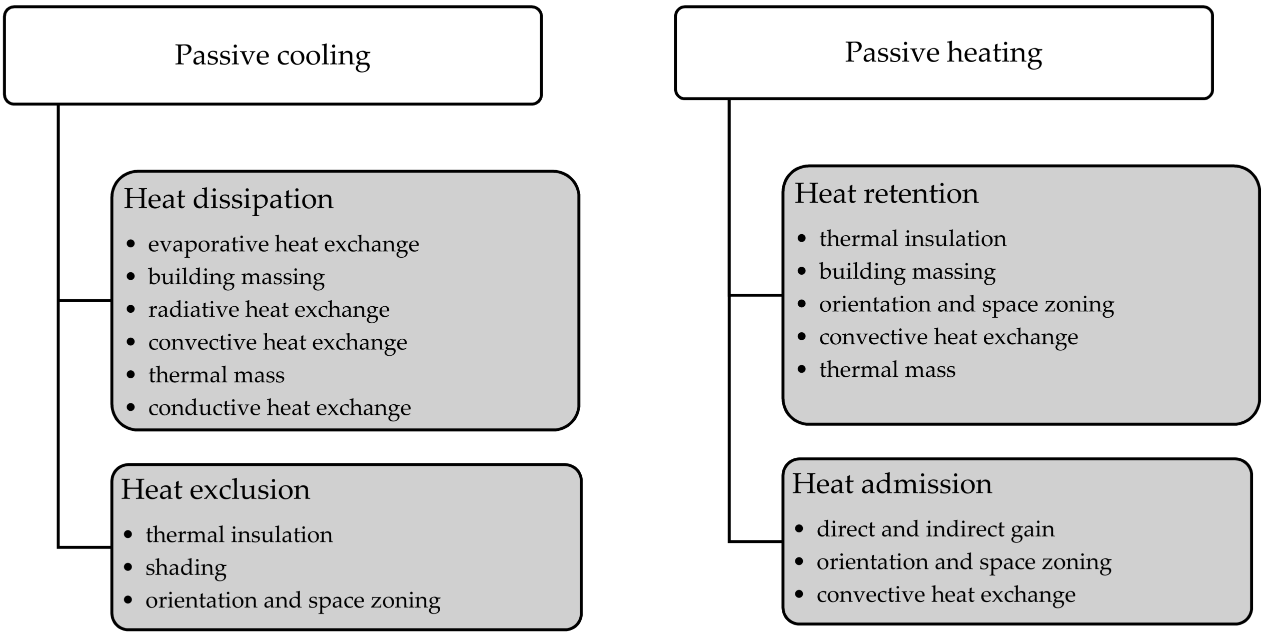

Figure 1. Bioclimatic architecture strategies—passive cooling and passive heating. Based on information obtained from Košir [12], extended using Lechner [13] and La Roche [14].

2.1. Orientation and Space Zoning

Following analysis of the local climate condition and site analysis, the first design step in passive solar design is to determine the building's orientation [15]. Orientation as the most important and most frequently studied parameter can reduce the need for conventional heating or cooling and enhance the performance of other passive strategies [16,17]. Sun angles, local wind directions and seasonal and diurnal temperatures are key to optimising orientation [15]. Attention should also be paid to on-site shading or other factors such as building shape, transparent areas or insulation levels which will influence later design stages [18] (Figure 2).

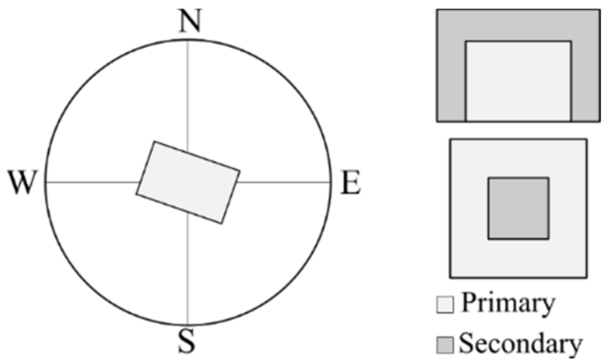

Figure 2. Building orientation (**left**) and space zoning (**right**).

One strategy to design the building layout is to use space zoning. Space zoning can influence both energy consumption and the quality of the indoor environment. The clustering of zones with a similar thermal environment as heat retention strategy was described by Košir [12]. Here secondary zones with lower comfort requirements surround the primary zones, buffering heat losses to the outside [12]. A contrasting strategy is to expose rooms with heating demand to solar radiation. Ideally, this is combined with transparent areas to maximise solar gains during the cold season [13] (Figure 2).

Keywords: "orientation", "building layout", "space zoning"

2.2. Building Massing

A vital part of the initial design process is defining the shape of a building [15]. This includes the aspect ratio and the compactness of the buildings. The aspect ratio is the ratio between building length and building width and provides information on the area exposed to solar radiation. The compactness expresses the ratio between building volume and external surface and indicates the heat storage capacity and possible heat losses and gains via the facade [16]. The compacter a building becomes, the lower the heat losses and vice versa (Figure 3).

Keywords: "building massing", "building volume", "compactness"

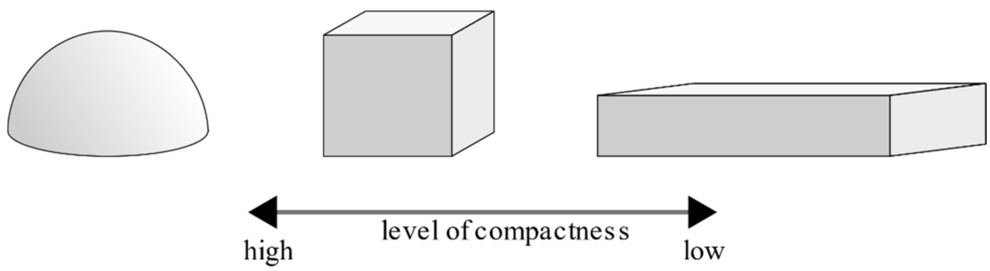

Figure 3. Building massing—level of compactness.

2.3. Thermal Mass

According to Song et al. [19], each material used in a building has different densities and heat storage and transfer abilities. The buildings' thermal mass is characterised by those properties and can store or release heat. Thermal mass can be used for both passive heating and cooling [19]. For passive heating, solar gains are usually used to heat the thermal mass during the day, which is then released during the night [20]. For cooling, the energy stored in the thermal mass during the day must be released during the night to be effective. An efficient energy releasing strategy could be natural ventilation [19]. Along with using typical building materials, such as concrete, phase-change materials (PCM) can be used to increase a building's thermal mass [8,19] (Figure 4).

Keywords: "thermal mass", "PCM"

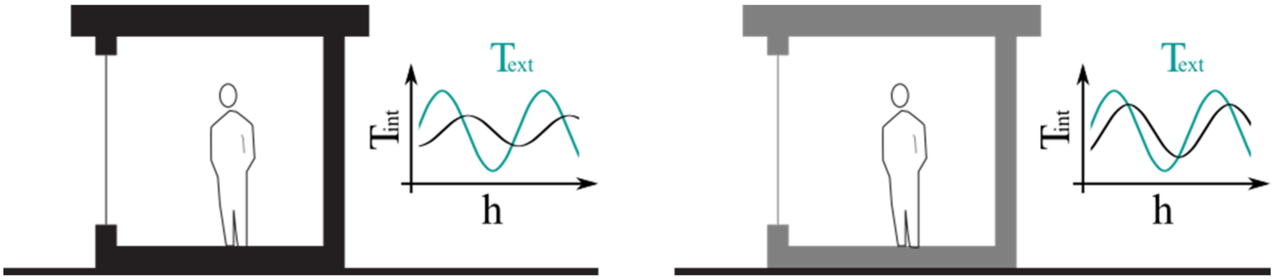

Figure 4. Thermal mass—heavy (**left**) and light construction (**right**).

2.4. Thermal Insulation

Thermal insulation is one of the main strategies to prevent heat losses. In temperate and cold climates, past and current legislation has been concerned with reducing the heating demand by insulating and air tightening the thermal envelope [4] thus achieving a low heat transfer coefficient (U), which is a measure for the heat loss per area of specific building components [16] (Figure 5).

Keywords: "thermal insulation"

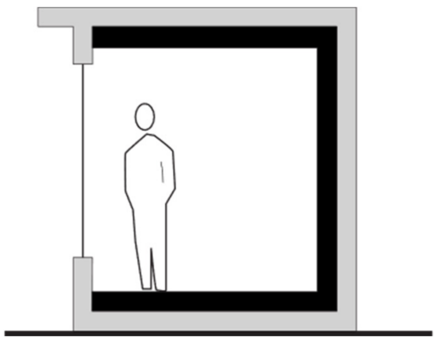

Figure 5. Thermal insulation.

2.5. Direct and Indirect Solar Gains

Using solar radiation is the simplest way to heat the building. Solar gains are "direct" when solar radiation enters through a transparent part of the building envelope and is stored in the rooms of the building. They may also be "indirect" when, for example, a sunspace or a Trombe wall is heated up, and warm air is circulated into the building [12–14] (Figure 6).

Keywords: "glazing", "window", "sunspace", "glazed space", "glazed balcony", "atrium", "wintergarden", "Trombe wall"; "solar wall"

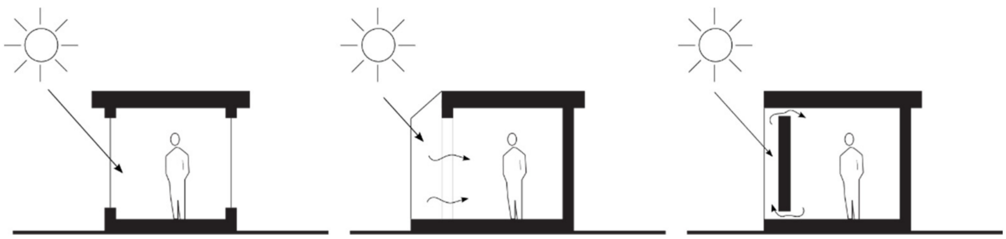

Figure 6. Direct and indirect gains—glazing (**left**), sunspace (**middle**) and solar/Trombe wall (**right**).

2.5.1. Glazing

As the transparent part of the facade, glazing contributes a high share to direct solar gains [17] and total heat losses [21]. Therefore, for climates with cold winters and warm summers, a balance between maximising direct solar gains in winter and minimising direct solar gains in summer must be found to reduce the conventional heating need without increasing the cooling demand.

Keywords: "glazing", "window"

2.5.2. Sunspaces

Sunspaces, also called winter gardens, can be glazed spaces attached to the building, atria or glazed balconies [13]. The space is heated up by solar radiation during a winter day. This space acts as a buffer zone between the outside and the inside during the night and thus reduces heat losses to the outside. In addition, warm air can be ventilated into the building, heating the occupied rooms of the building [17].

Keywords: "sunspace", "glazed space", "glazed balcony", "atrium", "winter garden"

2.5.3. Solar/Trombe Wall

A solar wall is a passive system that uses direct solar gains to heat a cavity between the outdoors glazing and a solid wall with high thermal mass. Next to heating the air in the cavity, the heat is absorbed and stored in the wall. The stored energy is then released by conduction to the room on the other side of the wall and by convection when vents are opened [22].

Keywords: "Trombe wall"; "solar wall"

2.6. Solar Shading

Solar shading systems aim to exclude solar radiation and thus avoid overheating in the building. Solar shading can be achieved by building geometry, vegetation or dedicated shading devices. Dedicated shading devices are further divided into fixed and moveable shading characterised by the colour, the used material and the position relative to the opening [15] (Figure 7).

Keywords: "solar shading", "sun shading"

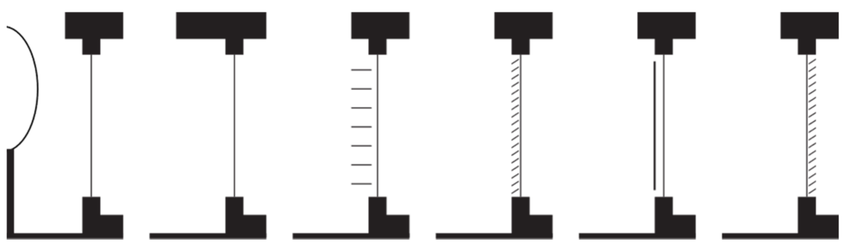

Figure 7. Solar shading—F.L.T.R. Vegetation, overhang, fixed horizontal slats, external venetian blind, external screen and internal venetian blind.

2.7. Convective Heat Exchange

When the indoor environment is too warm, and the comfort is compromised, the air movement around the occupants may be increased. This can be done using natural ventilation techniques often categorised as single-sided, cross and stack ventilation and windcatchers/wind towers [23–26] (Figure 8).

Keywords: "natural ventilation", "ventilative cooling", "windcatcher", "wind tower"

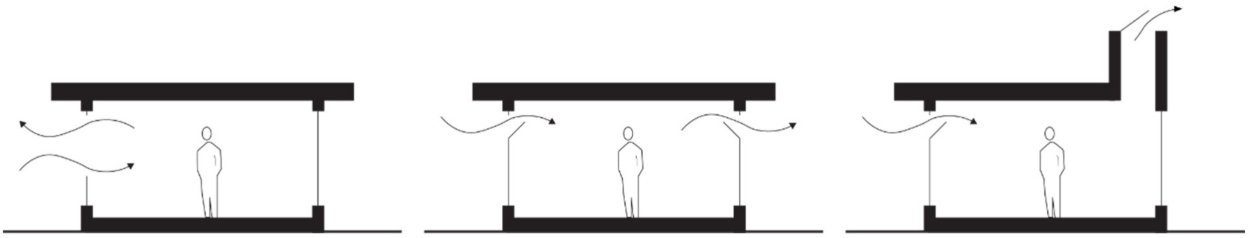

Figure 8. Natural ventilation—single-sided ventilation (**left**), cross ventilation (**middle**) and stack ventilation (**right**).

2.8. Conductive Heat Exchange

The soil, which has a relatively stable temperature, may provide a cooling and heating possibility for a building. Thereby, earth sheltering can reduce outside air infiltration, provide additional thermal resistance and reduce solar and convective heat gains [27] (Figure 9).

Keywords: "conductive cooling", "earth cooling", "soil cooling", "earth berming", "earth coupling", "earth sheltering", "ground cooling"

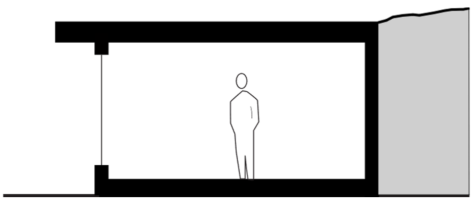

Figure 9. Conductive heat exchange.

2.9. Radiative Heat Exchange

Radiative cooling uses the cold sky during the night as a sink [13,19]. According to Lechner [13], radiative cooling works best in dry and hot climates with clear skies during the night. One strategy for utilising direct radiative cooling is to build the roof out of concrete, expose it during the night and cover it with insulation during the day. The concrete then acts as a sink and thus cools the building [13]. Instead of concrete, water bags can be used as well [19] (Figure 10).

Keywords: "radiative cooling"

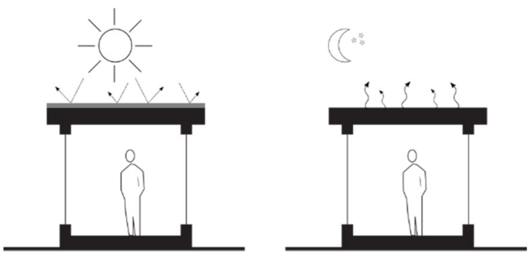

Figure 10. Radiative cooling—day (**left**) and night (**right**).

2.10. Evaporative Heat Exchange

Direct evaporative cooling uses water evaporation whereby the water absorbs the heat from the dry and warm air. As a result, the air temperature drops, and the relative humidity is increased [28]. The technique works especially well in dry and hot climates, whereas its effectiveness is reduced in cold and humid climates due to the already high water saturation of the air [28] (Figure 11).

Keywords: "evaporative cooling"

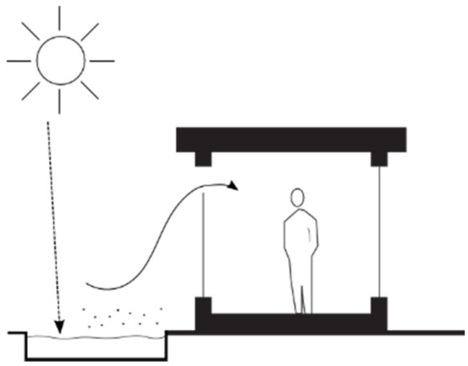

Figure 11. Evaporative cooling.

3. Methods

First, a literature review is conducted to provide an overview of Denmark's already investigated passive strategies. Second, a selection of Danish building projects using passive strategies is presented. Sections 3.1 and 3.2 specify the criteria used for the literature review and present the selection process for Danish building projects. While the literature review results aim to present a comprehensive overview of all existing investigations fulfilling the below-stated criteria (see Section 3.1), the presentation of the Danish building projects represents only a selection of past years.

3.1. Selection of Relevant Literature

Web of Science, Scopus and Google Scholar were searched for relevant articles. The keywords defined in Section 2 were used combined with "Denmark" and "Danish" using "AND". If the keywords were not unambiguously related to buildings, the word "building" was added to reducing the number of search hits. Title, author keywords and abstracts were searched for Web of Science and Scopus. In Google Scholar, the whole article was searched. Citations were excluded, and the results sorted according to their relevance (set by Google). Keyword groups were searched within quotes (" . . . "). Due to the enormous amount of search hits in Google Scholar, only the first 200 were screened if the search hits exceeded 200. In Web of Science, all relevant keyword groups belonging to one topic were searched at once, whereas each keyword group was searched individually at Scopus and Google Scholar. The databases were searched in the following order: (1) Web of Science, (2) Scopus and (3) Google Scholar. Duplicates were only removed from the resulting search hits if they were sought for retrieval in the previous database or keyword search, meaning that non-retrieved publications can be included in the identified and screened records multiple times.

Furthermore, a citation search of the relevant publications was conducted. The search was done during calendar weeks 32–34 (2021). The papers for retrieval were selected based on title and abstract for Web of Science and Scopus and based on title and displayed paragraph in Google Scholar. The articles' eligibility was based on the full article. For both steps, the following criteria were applied:

- matching the keywords
- investigation was located in Denmark

- journal article, conference proceeding, technical report or PhD thesis
- English language publication
- any kind of building typology and building usage
- any study types (field study, experiment, simulation, etc.)
- passive strategy was the (or one of the) main investigation focus/foci of the study
- passive strategy evaluated for energy consumption and/or indoor environmental quality and/or environmental parameters and/or architectural quality

The search is documented using the updated PRISMA flowchart (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) by Page et al. [29], based on the flowchart by Liberati et al. [30]. For each passive strategy search, one PRISMA diagram was created. An example diagram can be seen in Figure 12. The remaining diagrams can be found in Appendix A. The only valid reason for non-retrieval of publications was that access to the article was not possible. The characteristics of the studies included in the literature review are summarised in Table A1 (for the table, please see page 14).

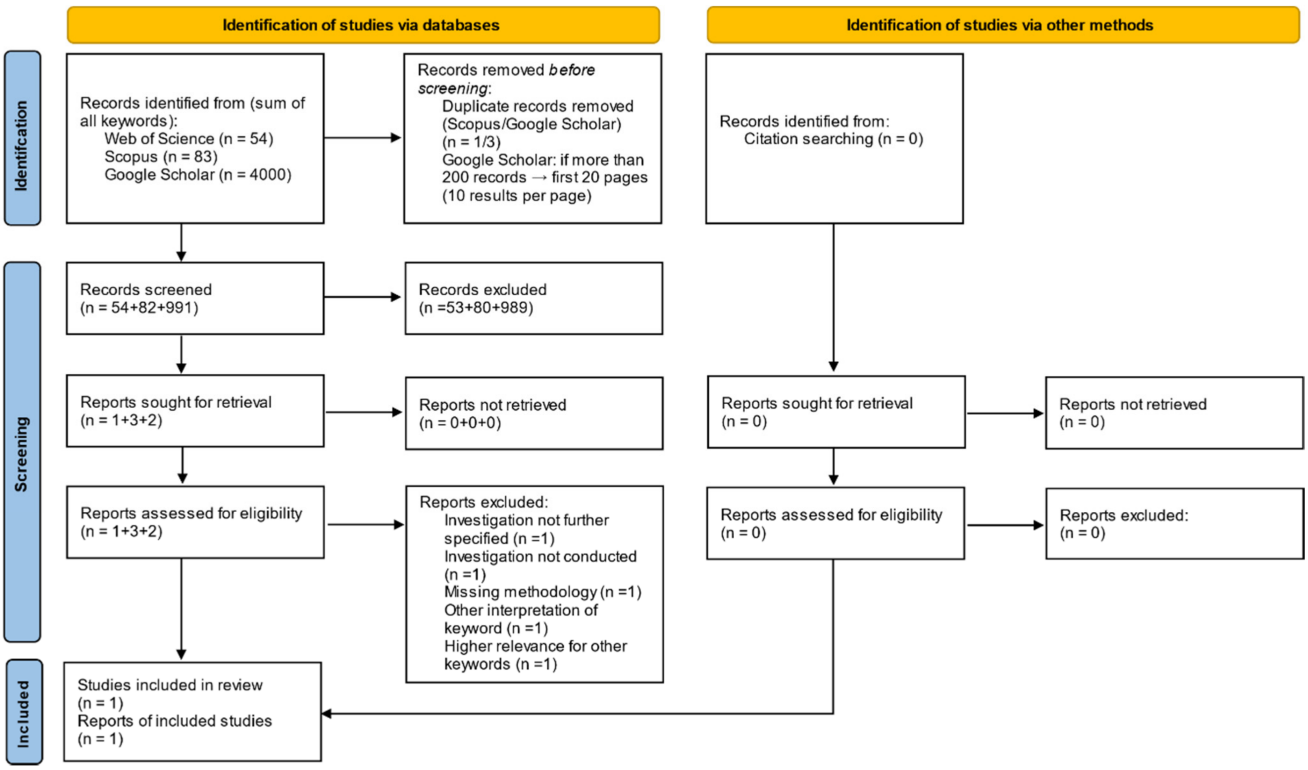

Figure 12. Example PRISMA diagram for keywords "orientation", "building layout" and "space zoning".

3.2. Selection of Danish Building Projects

Architectural magazines, books (online and printed) and web pages were used for this section. No specific search technique was applied. Only the bioclimatic architectural aspects, mentioned within the description of the project are presented. It is to be noted that a conflict of interest of the authors reporting the characteristic of the individual building project cannot be ruled out for all the used references (listed in Table A2). Each project is characterised by the keywords identified in Section 2.

4. Results

In total, 49 (52 different investigations) publications were found to be relevant for the investigation of bioclimatic architectural strategies in Denmark. No relevant literature was identified regarding the following keywords:

- "building layout", "space zoning"
- "atrium", "wintergarden"
- "Trombe wall"
- "conductive cooling", "earth cooling", "soil cooling", "earth berming", "earth coupling", "earth sheltering", "ground cooling"

The strategies reviewed included thermal mass, thermal insulation and natural ventilation as the most researched passive strategies, and space zoning and conductive heat exchange as the least (Figure 13).

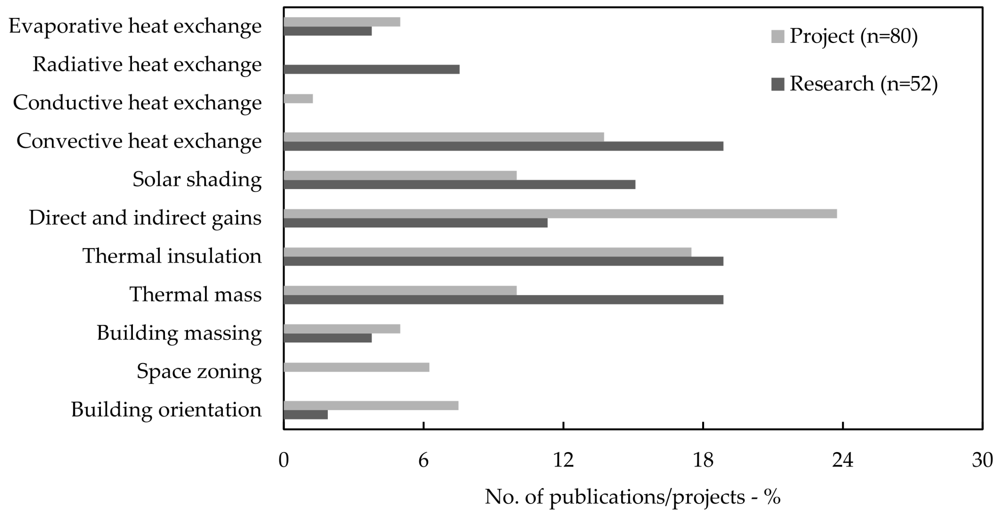

Figure 13. Comparison of the number of investigated and built passive strategies.

Most of the studies were conducted on residential buildings with a view to evaluating energy consumption and/or thermal comfort. Furthermore, the review showed that the research interest in passive cooling started in 2007 shortly after the new Danish building regulations of 2006 entered into force (Figure 14). In these new building regulations, it was demanded that cooling energy and overheating be evaluated [4]. Research interest was balanced between passive cooling and passive heating strategies after 2007, as reflected in an equal number of investigations of either strategy until today (Figure 14). However, interest in passive cooling seems to have declined in recent years, whereas interest in passive heating has increased. A large number of investigations contributing to this increase are concerned with the energy flexibility and load shift potential of buildings. As this topic relates to the use of thermal mass as a passive strategy, it is discussed there.

Twenty-five building projects were reviewed. All projects are listed in Table A2 (for the table, please see page 20)—nearly all projects used at least two passive strategies. Most of the passive strategies were devoted to direct and indirect gains by windows and atria, natural ventilation by window opening and thermal insulation. In contrast, conductive heat exchange and radiative heat exchange were the least mentioned. Furthermore, it was seen that passive heating strategies were used in nearly every project throughout all years of construction, whereas passive cooling strategies were continuously implemented from 2006 onwards (see Table A2), presumably as a result of the introduction of the new Danish building regulations [4]. The integration of the passive cooling strategies was mostly seen for non-residential buildings.

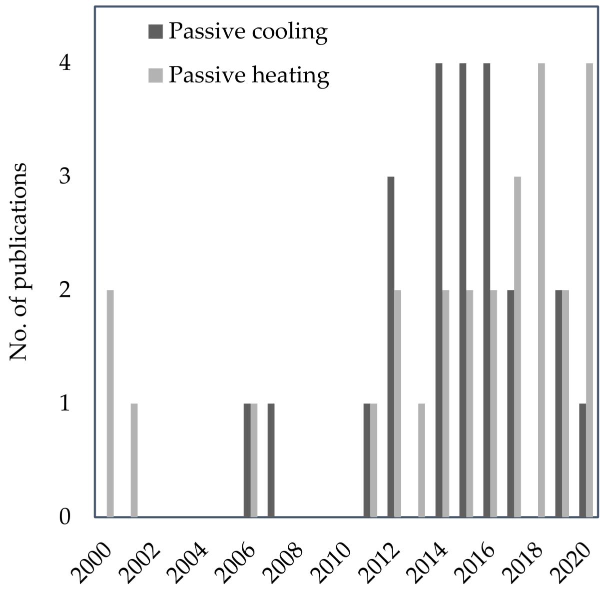

Figure 14. Number of publications per year.

Focusing on the individual strategies, it can be said that despite the initial claim that orientation is one of the most studied parameters for passive solar design [16], only one Danish study was identified [31]. Here it was shown that the orientation has an impact on the overheating magnitude in the studied object. Even though not investigated, this statement was also made by other Danish researchers [4,32]. Among the built projects, several buildings were oriented towards a specific orientation—mostly south with the primary purpose being to enhance thermal comfort and the reduce energy need [33–38]. It could be further seen that the projects taking orientation as a passive strategy into account were predominantly residential buildings. No trend was seen in regard to the year of construction as the strategy was applied for buildings built in 1854 as well as for today's buildings.

Space zoning was never investigated but mentioned several times as a strategy for built projects. Here, the strategy was applied by surrounding common rooms with rooms that need less heating and creating buffer zones in the shape of atria [33,36,38,39]. The strategy was applied equally for residential and non-residential buildings whereby space zoning in non-residential buildings was always implemented using an atrium which additionally enhanced indirect gains. Conductive heat exchange was also never investigated but was implemented once for an examined building project that used stable ground temperatures in colder periods to heat the common room of the multi-family home [38].

Building massing was investigated in the urban context, where a significant impact on energy consumption was shown [40,41]. Moreover, the strategy was mentioned in three of the screened projects, which aimed to decrease heat losses by reducing the surface area [33,38,39,42]. Here no tendency towards a specific building typology or year of construction could be identified.

Thermal mass in construction was studied in research from different perspectives. With a significant focus on energy flexibility, researchers presented the potential of high thermal mass in low-energy buildings to maintain comfortable indoor conditions for hours [43,44]. In contrast, another investigation showed that the slightly lower energy consumption of the high thermal mass is outweighed by the in total lesser CO_2 emissions of the low thermal mass [45]. Further, studies about thermal mass in PCM shape were presented, showing that they can reduce heating and cooling energy [46,47]. An equal number of studies concerning thermal mass were seen for single-family houses and multi-story houses. In contrast, only two investigations were conducted for non-residential buildings. In addition, even though the concept of using thermal mass as a passive strategy is not new, as already 2001 one study dealt with this topic [45], a drastic increase in research was seen in the past five years. In those studies, the focus was on load shift potential and energy flexibility [43,44,48–52] with the idea to use the building as passive thermal energy storage [50]. This passive thermal energy storage can then compensate for variations of renewable energy source production in an integrated Smart Grid system. According to Johra, Heiselberg and Dréau [50], this can further improve the controllability of the energy grids, making the integration of renewable energy sources easier. In practice, several projects mentioned an active decision for high thermal mass to increase comfort and decrease the need for cooling and heating [10,34,38,53–55]. The strategy was mentioned more often for residential buildings built after 1985.

The literature dealing with thermal insulation in Denmark investigated the effect of new insulation requirements and increasing thickness on the architectural design and indoor comfort. It was found that traditional ways of designing must be rethought as the rising insulation thickness influences the spatial demand [56] and that an increased level of insulation and direct solar gains can lead to overheating [10]. Moreover, it was focused on renovation projects, where various renovation measures such as insulation of the main building components, the improvement of windows and the general energy-saving potential for the whole of Denmark were the major focus. Next to the high general energy-saving potential of a renovated building stock [57,58], the insulation of the main opaque and transparent components was seen as the most effective but not always as the most economical one [59–64]. The studies were equally conducted for residential and non-residential buildings whereby the focus on applying thermal insulation as a passive strategy to reduce energy consumption was larger than the one on newly built buildings. Thermal insulation was one of the most mentioned heat retention strategies to reduce heating energy for building projects [10,35–38,42,54,65,66]. The strategy was equally applied to residential and non-residential buildings and continuously implemented from 1991 on.

Windows were studied for new buildings and renovations. They concerned glazing-to-floor ratios, distribution of the window-to-floor ratio and physical properties of the glazing, and apart from one study [67] they dealt with residential buildings. Due to the current insulation requirements, the importance of a large window area is reduced as the effect on the heating energy is small, and a low U-value is more important than a large window area [68,69]. Further, it was seen that window replacement is a suitable strategy for renovations to decrease the heating demand [70]. Another studied topic was the sunspace, which was suitable for reducing the energy demand when they were unheated [71]. In addition, one study investigating the yield and profit of a solar wall showed that this strategy is economical and has an even higher economic potential in the future when energy prices rise [34]. Direct and indirect gains were mentioned for nearly all built projects to either enhance the daylight or increase solar gains. Thereby solar gains were obtained using windows, sunspaces, solar walls and atria [10,34,36–39,42,53–55,57,65,66,71–73]. Atria was implemented for residential as well as non-residential. In contrast, sunspaces were only applied to residential buildings.

The effect of solar shading was investigated in terms of energy consumption and thermal comfort for residential and office buildings. It was found that shading can successfully reduce the hours above the comfort limit [31,74,75] and further has an influence on the energy consumption of the building [21,76,77], whereby the dynamic and moveable shading was favoured [31,77]. For the built projects, solar shading was mostly implemented in offices buildings [35,39,42,53–55,65,78]. The reason for this could be the aim to reduce the cooling demand caused by the high internal heat loads and the large, glazed areas which are commonly used in Denmark to increase daylight availability during winter months. Moreover, it could be seen that solar shading is a relatively "new" passive strategy for Denmark as it was not implemented before 2009 and researched before 2011.

Natural ventilation was one of the most researched. It can be said that there is a high potential for increasing thermal comfort in summer and reducing the energy demand in Denmark. The strategy worked well for all kinds of residential buildings [54,65,79,80] but in schools was less satisfying than mechanical ventilation as the CO_2 concentration could not be kept below the limit [81,82]. Apart from that the strategy was investigated for a shopping centre [83], a kindergarten [65] and an office [83]. The year of construction reached thereby from the 1970s over renovated buildings to today's active and passive houses. In practice, natural ventilation methods were frequently implemented primarily without stating the natural ventilation strategy to ensure a certain airflow [33,36,37,39,53–55,65,72,73,78]. They were equally applied to residential buildings and non-residential buildings, and further, it could be seen that the strategy was also used in older buildings.

Radiative cooling was studied together with unglazed solar collectors and photovoltaic/thermal panels, where the studies did not agree on the applicability of this aperture for Denmark [84–87]. This strategy was only investigated and recommended for use in non-residential buildings. In addition, it can be said that it is a relatively new strategy in Denmark, as the first study was conducted in 2015 [87]. In practice, radiative cooling was not considered by any building project. Moreover, evaporative cooling was investigated in two different setups for the Danish context. Both studies found that the indoor temperature was significantly lower for systems with evaporative cooling compared to one without [88,89]. As a disadvantage, it was argued that the system performance depends on the outdoor air condition and is not economically competitive. As for radiative cooling, it could be seen that evaporative cooling was only investigated for non-residential buildings, with the first publication in 2015 [89]. For the built examples, evaporative cooling was created mainly by surrounding vegetation and green roofs [39,42]. It was only applied in non-residential buildings with the first project in 2011.

5. Discussion and Conclusions

This paper presented a detailed systematic review of theoretical studies investigating commonly used bioclimatic architecture in the Danish climate besides an overview of 25 actual building projects in Denmark. The outcome shows that almost all considered passive strategies are used in Denmark, whereby the focus is on passive heating strategies. The passive heating focus lies on direct and indirect gains, thermal insulation and thermal mass, where around 70% of the studies concerning residential buildings and around 35% of the studies concerning non-residential buildings focused on those three passive strategies. It is expected that the passive heating measures—in particular, thermal insulation and thermal mass—will maintain their current research interest for residential buildings in the perspective of energy flexibility but also will gain more importance as a passive cooling strategy. The research regarding direct and indirect gains which were mainly investigated and applied in residential buildings will presumably focus more on achieving a balance between contributing to heating demand reduction and cooling demand increase. It can be assumed that they will be increasingly investigated and applied together with solar shading. Further, their importance to residential buildings will stay similar to today's, whereas the importance for non-residential buildings will be at the same low level as it is at this time.

The passive cooling focus lies on natural ventilation and solar shading, where around 30% of the studies investigating residential buildings and around 40% of the studies investigating non-residential were concerned with those two strategies. For non-residential buildings, evaporative and radiative cooling account for an additional 24% of the studies, which increases the share of passive cooling strategies. Due to the increasing temperatures, it is expected that the trend towards using bioclimatic architecture strategies for cooling will become more and more popular in Denmark, especially for non-residential buildings such as offices. Even though the attention of studies concerning residential buildings is currently focused on passive heating strategies, few studies have already shown that new and renovated residential buildings show high indoor air temperatures during the summer season [31,66,74]. Consequently, research towards cooling passive design strategies for residential buildings is expected. Here, solar shading, despite the equal number of investigations for residential and non-residential buildings, could be an effective strategy. Still, the application on built projects is shifted towards non-residential buildings. Next to this, natural ventilation is a strategy that is investigated and applied in both residential and non-residential. Its use should be further promoted, as it is a simple and cheap strategy to enhance summer thermal comfort. One other possibility to enhance thermal comfort in residential buildings that were neither applied nor researched is evaporative cooling by vegetation. As the applicability of radiative cooling within the researched setup was not clear, it is not expected to have any relevance when it comes to cooling the residential building stock. Among the studied buildings, renovations made up around 20%, which shows that passive strategies are not limited to newly built buildings. Due to this, it can be said that the potential of using all bioclimatic architecture strategies for renovations in Denmark, concerning the increased amount of refurbishment projects [90], is significant, as they provide the chance to waive and replace active heating and cooling measures and thus decrease the energy consumption of the building stock.

Even though the literature search was conducted to the best of the author's knowledge, it still has limitations that need to be taken into account when considering this article. First, the search was conducted in English, only considering publication written in English. As the study concerned Denmark, there is a potential for similar investigations to be conducted in Danish. Further, the search combined the keywords with "Denmark" and "Danish", implying those keywords are stated within the publications' abstract or title (for Scopus and Web of Science) or the complete publication (Google Scholar). Articles only mentioning a specific location in Denmark and not the country itself are thus not included in the study.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. PRISMA Flowcharts

Appendix A.1. Building Orientation

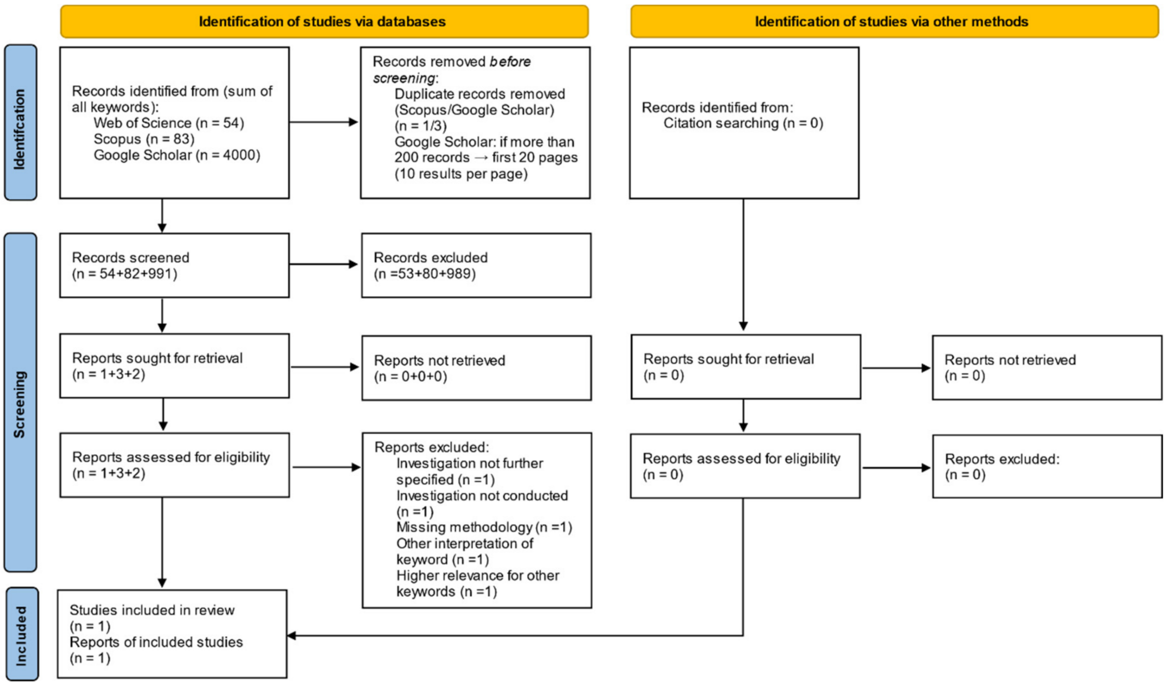

Figure A1. PRISMA diagram for keywords "orientation", "building layout" and "space zoning".

Appendix A.2. Building Massing

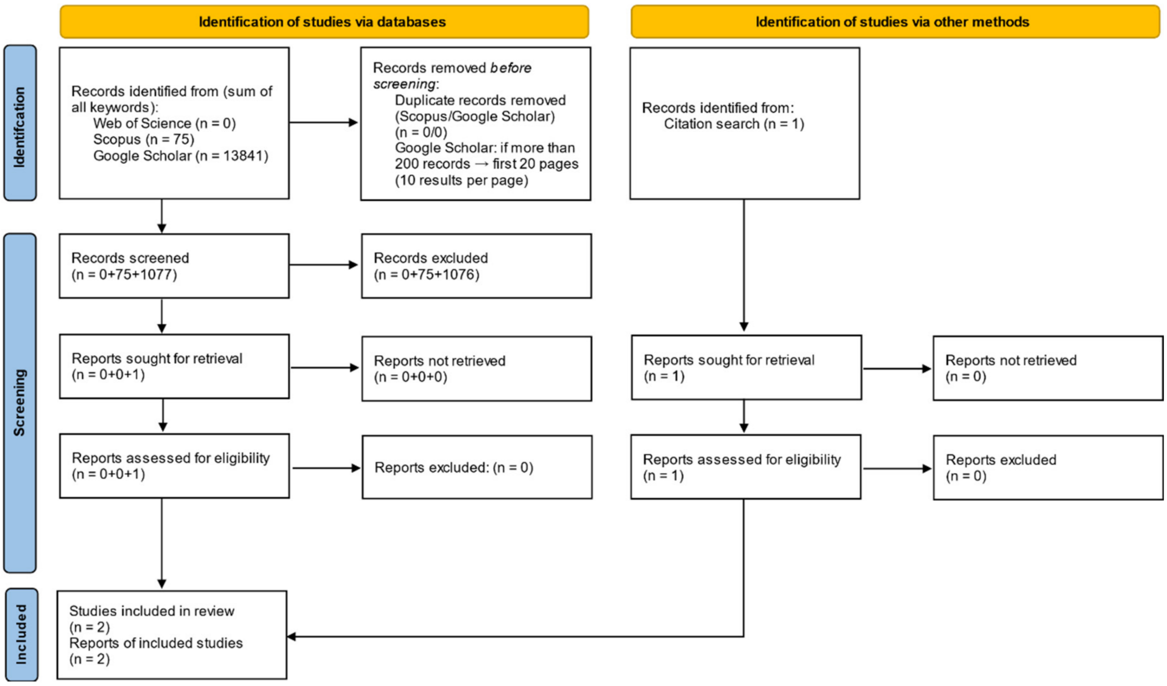

Figure A2. PRISMA diagram for keywords "building massing", "building volume" and "compactness".

Appendix A.3. Thermal Mass

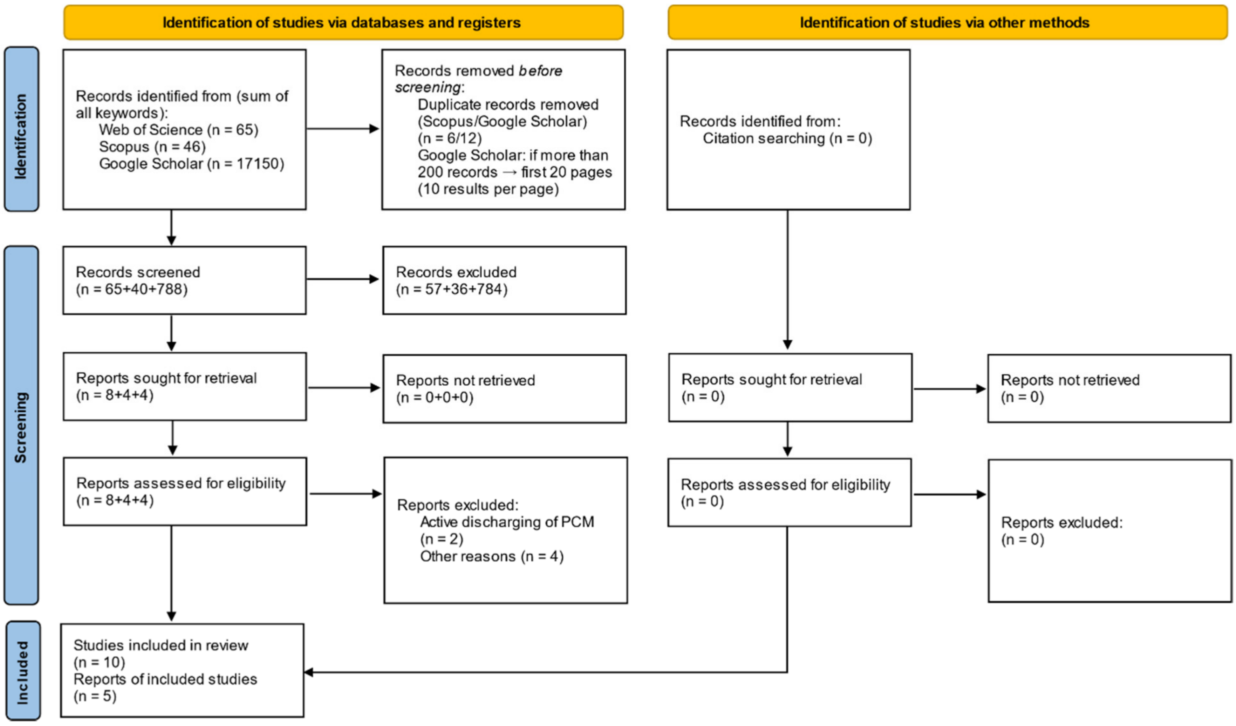

Figure A3. PRISMA diagram for keywords "thermal mass" and "PCM".

Appendix A.4. Thermal Insulation

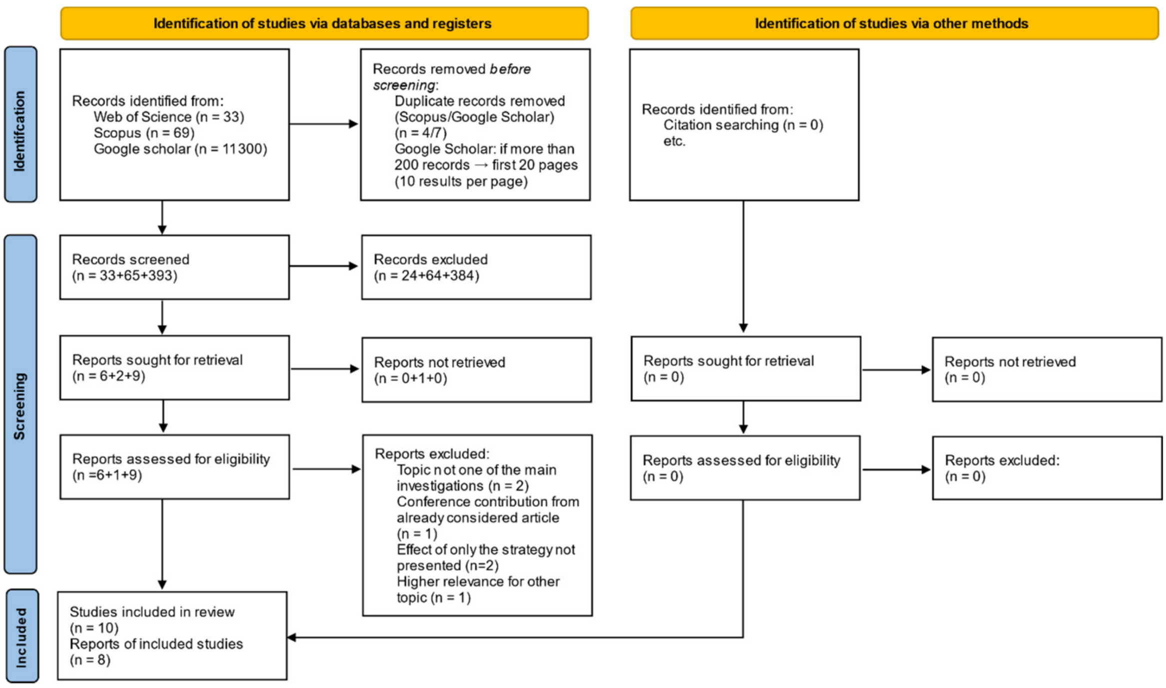

Figure A4. PRISMA diagram for keyword "thermal insulation".

Appendix A.5. Direct and Indirect Gains

Appendix A.5.1. Windows

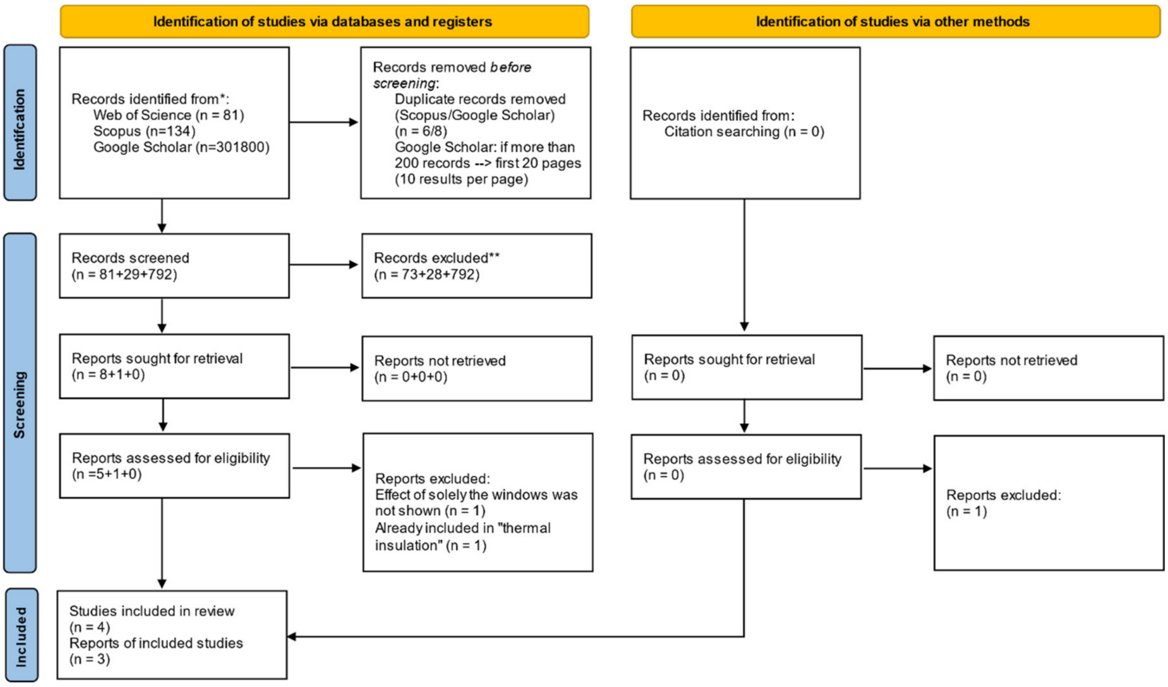

Figure A5. PRISMA diagram for keywords “glazing” and “window”.

Appendix A.5.2. Sunspace

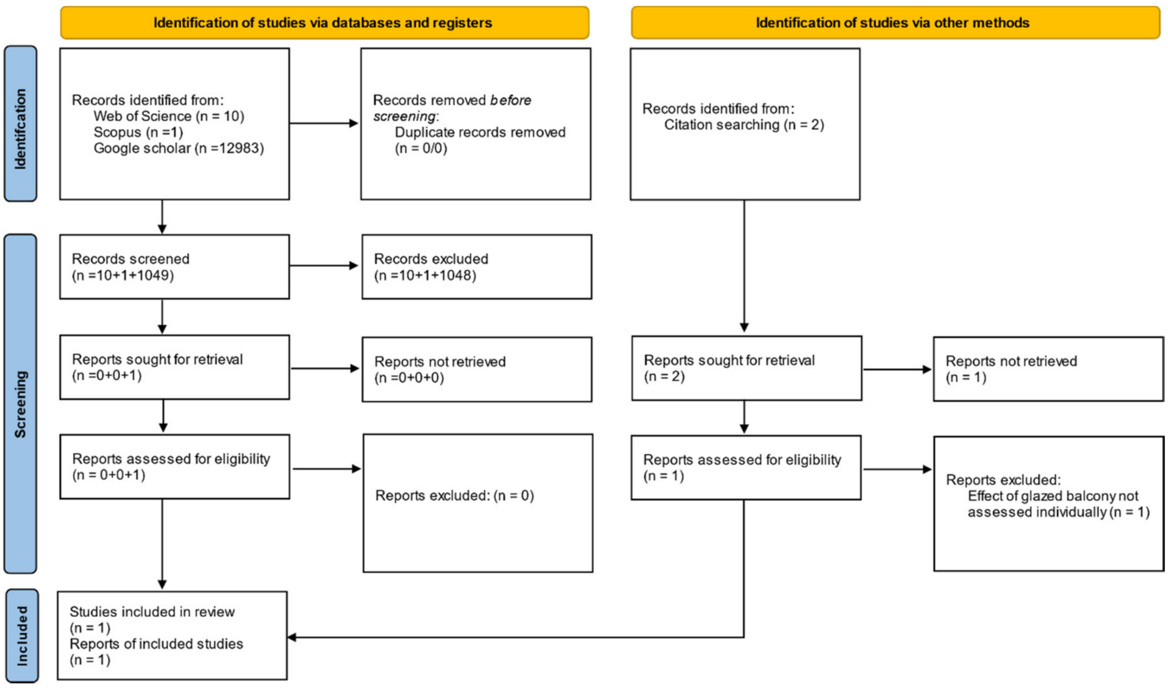

Figure A6. PRISMA diagram for keywords “sunspace”, “glazed space”, “glazed balcony”, “atrium” and “wintergarden”.

Appendix A.5.3. Solar Wall/Trombe Wall

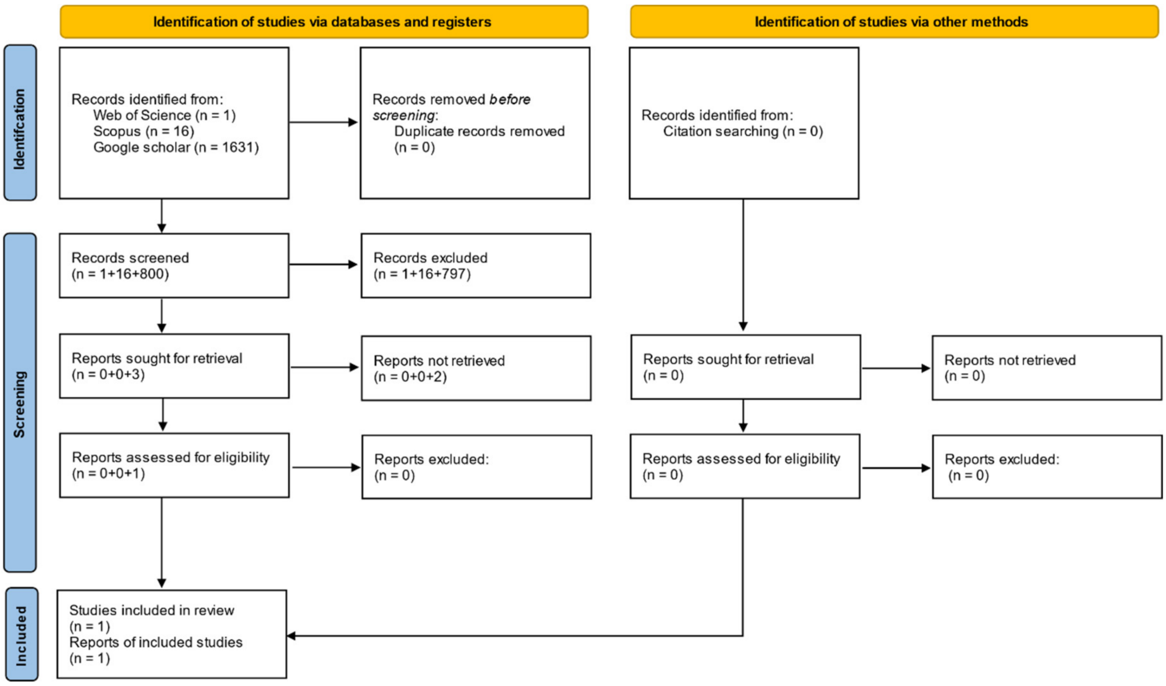

Figure A7. PRISMA diagram for keywords "Trombe wall" and "solar wall".

Appendix A.6. Solar Shading

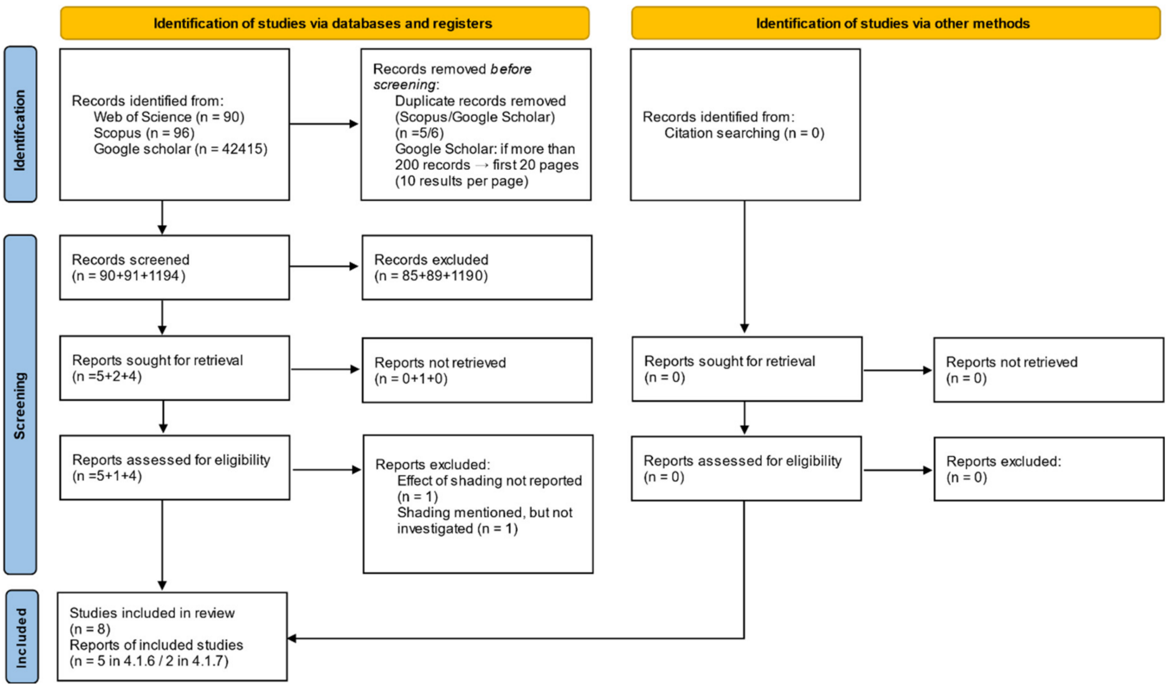

Figure A8. PRISMA diagram for keywords "solar shading" and "sun shading".

Appendix A.7. Convective Heat Exchange

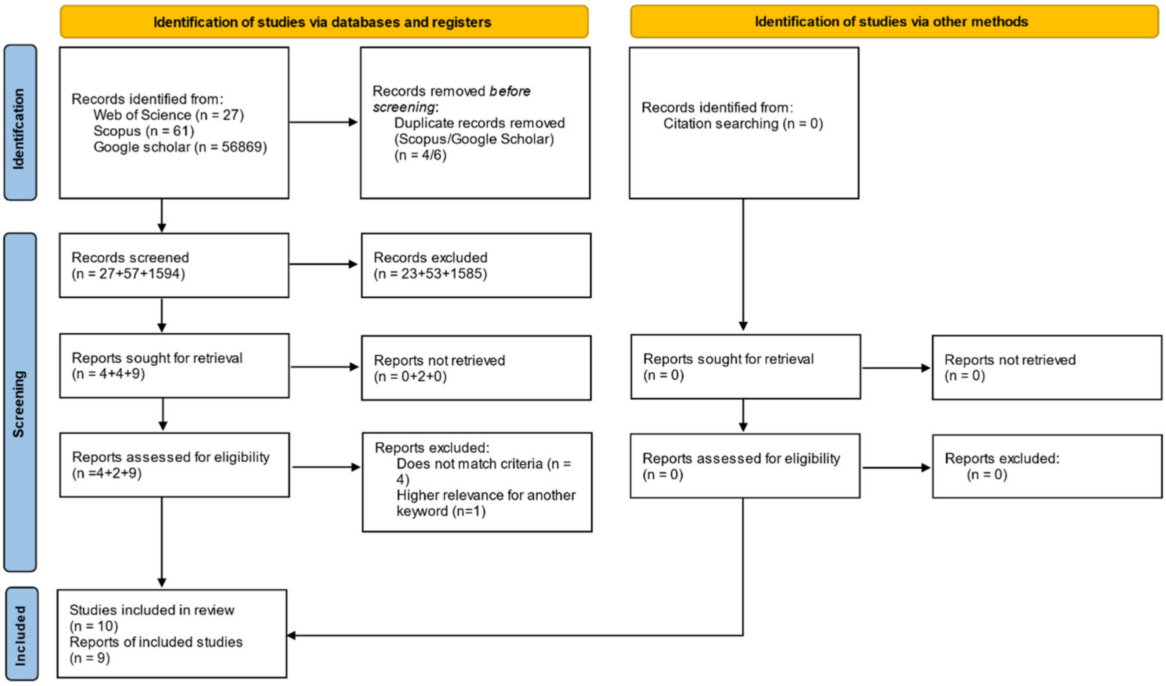

Figure A9. PRISMA diagram for keywords "natural ventilation", "ventilative cooling", "windcatcher" and "wind tower".

Appendix A.8. Conductive Heat Exchange

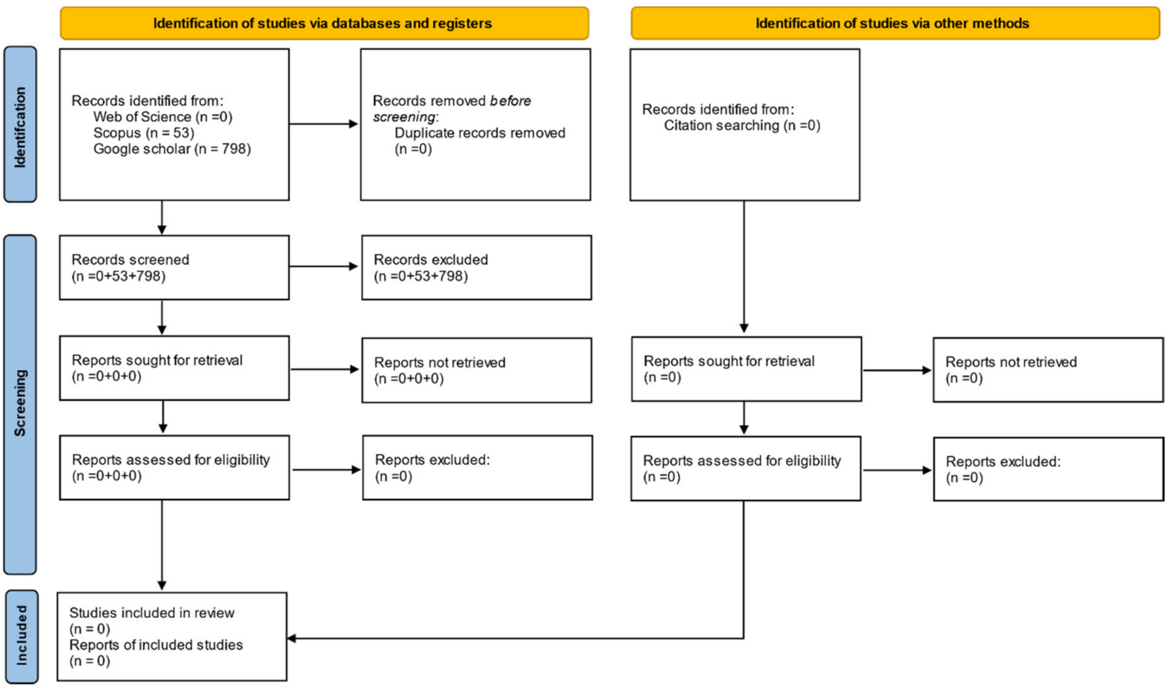

Figure A10. PRISMA diagram for keywords "conductive cooling", "earth cooling", "soil cooling", "earth berming", "earth coupling", "earth sheltering" and "ground cooling".

Appendix A.9. Radiative Heat Exchange

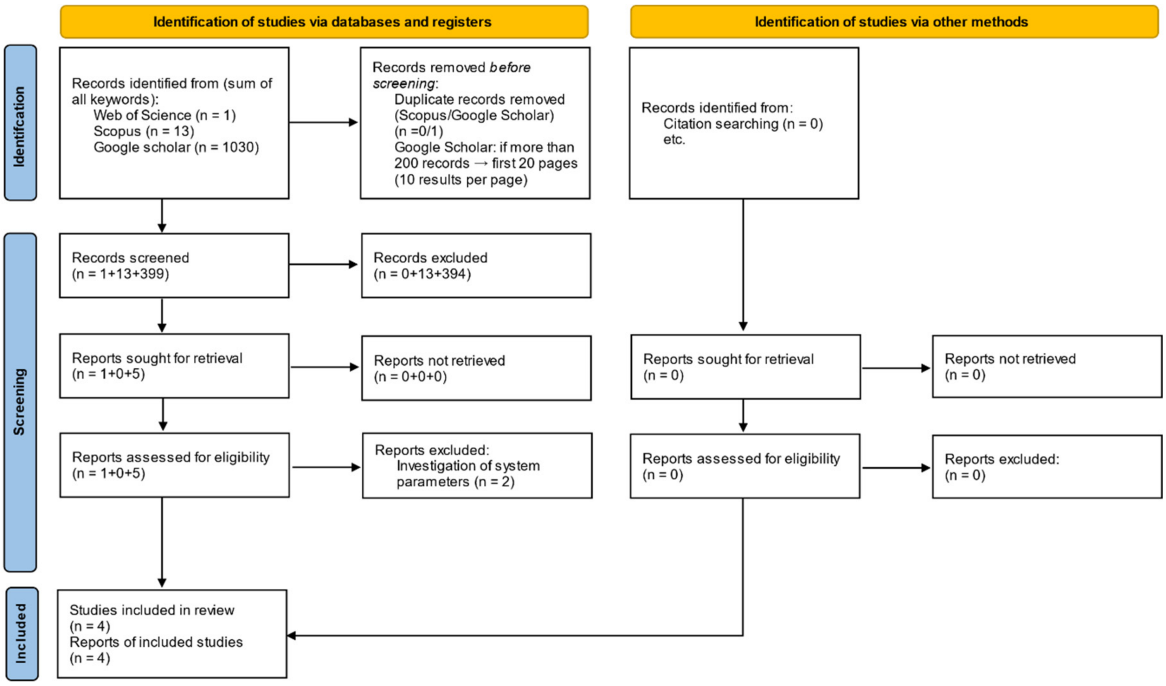

Figure A11. PRISMA diagram for keyword "radiative cooling".

Appendix A.10. Evaporative Heat Exchange

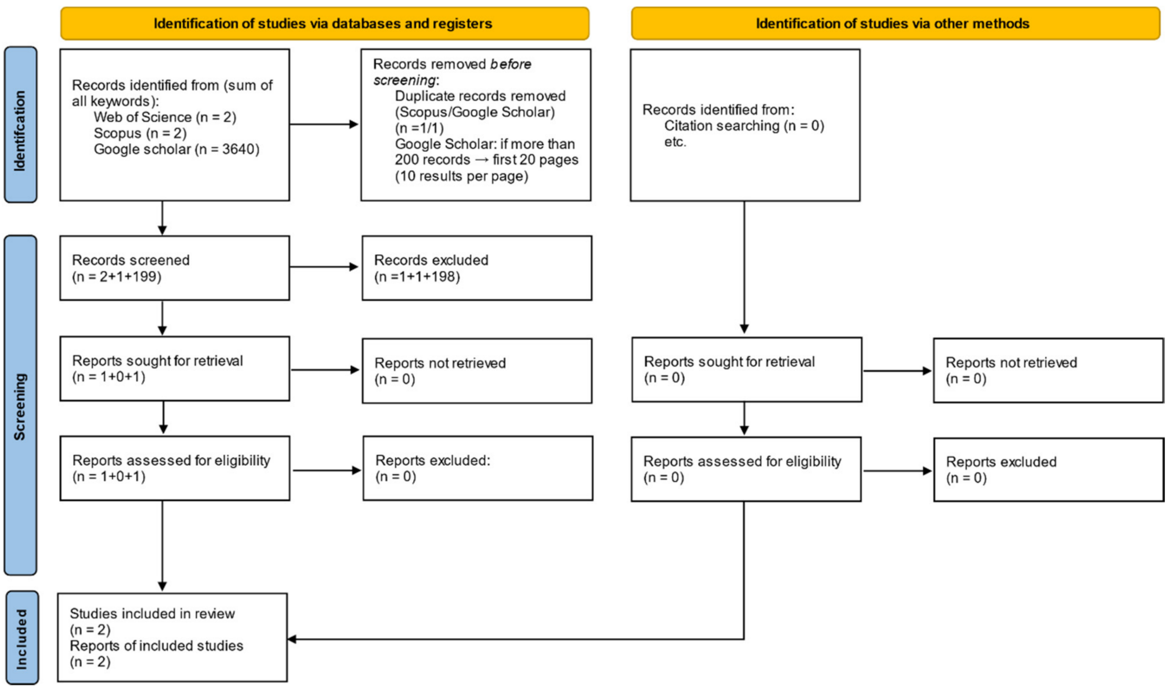

Figure A12. PRISMA diagram for keyword "evaporative cooling".

Appendix B

Appendix B.1

Table A1. Study characteristics and investigated passive strategy. Ordered according to their passive strategy and publication year.

Passive Strategy	Publication Year	Publication Type	Project Location	Research Aim	Study Type	Building Type	Construction Year	Evaluation Criteria	Ref.
Orientation									
O, SS	2019	c	Copenhagen	Solar shading potential evaluation to reduce overheating.	BPS	multi-storey residential	1850–1900 (renovated)	energy consumptionthermal comfort	[31]
Building massing									
BM	2011	ja	Copenhagen	Effect of urban canyons on building energy demand.	BPS	multi-storey residential multi-storey office	20th and 21st century	energy consumption solar gain	[41]
BM	2013	ja	Copenhagen	Passive solar energy and daylight impact on the energy performance of typical urban typologies.	BPS	multi-storey residential	20th and 21st century	energy consumption solar gain	[40]
Thermal mass									
TM	2001	ja	Copenhagen	Environmental impact of building materials and effect of thermal mass.	LCA	two-storey residential	late 20th century	energy consumption environmental parameters	[45]
TM	2016	c	Copenhagen	Assessment of load shift potential of low energy building.	BPS	multi-storey residential	2016	energy consumption indoor temperature	[43]
TM	2016	ja	Copenhagen	Evaluation of the amount of modulated heat and the effect duration on the grid comparing a building from 1980 and a passive house.	BPS	single-family houses	1980s passive house	energy consumption indoor temperature	[44]
TM	2018	ja	DRY	Quantification of physically available energy flexibility and identify the role of low energy buildings in the future energy system.	BPS	single-family house multi-storey residential	BR15 conform	energy consumption indoor temperature	[48]
TM	2018	c	Copenhagen	Investigation of potential demand-side flexibility of low energy buildings.	BPS	multi-storey residential	according to 2020 regulations	energy consumption indoor temperature energy balance	[49]
TM	2019	c	Copenhagen	Investigation of energy flexibility potential of office buildings built in different periods.	BPS	multi-storey office	1890–2020	energy consumption	[51]
TM	2019	ja	Copenhagen	Capacity evaluation of single-family houses to shift their heating demand.	white box model	single-family house	1980s passive house	energy consumption	[50]
TM	2020	c	DRY	Ability evaluation of houses to move heating energy use outside peak hours by simulating the thermal capacity.	BPS	single-family house	1850–1998	energy consumption costs	[52]
TM (PCM)	2020	ja	Aalborg	Measuring the thermal and energy performance of a window with integrated PCM for heating and cooling mode.	Measurement	two windows towards south	-	energy consumption inlet temperature	[47]
TM (PCM)	2020	ja	Odense	Simulation of PCM integrated into the building envelope.	BPS	single-storey office multi-storey office single-storey residential two-storey residential	BR18 conform	energy consumption indoor temperature	[46]

Table A1. *Cont.*

Passive Strategy	Publication Year	Publication Type	Project Location	Research Aim	Study Type	Building Type	Construction Year	Evaluation Criteria	Ref.
Thermal insulation									
TI	2005	c	Denmark	Technical and economic potential evaluation of energy savings.	N/A	multi-storey residential single-family house	1960–1970	energy consumption	[57]
TI	2006	c	DRY	Quantification of the impact of new regulations on newly designed buildings.	BPC	single-family house	BR06 conform	energy consumption	[56]
TI	2012	ja	DRY	Evaluation of the impact of climate mitigation on the adaption of Danish residential buildings.	BPC	two-storey terrace house	BR06 conform	energy consumption thermal comfort	[10]
TI	2012	ja	Copenhagen/DRY	Presentation of demonstration project where energy retrofitting measures were conducted.	Field study BPC	multi-storey residential	1896	energy consumption surface temperatureeconomy	[62]
TI	2014	c	Denmark	Calculation of possible energy savings of upgraded building components until 2050.	degree-day method	whole building stock	renovation BR10	energy consumption	[58]
TI	2015	c	Denmark	Evaluation of energy-saving potential by insulating exterior facade segments.	FEM analysis	multi-storey residential	1850–1930	energy consumption	[64]
TI	2017	c	Aarhus	Development of a new methodology for energy renovation of building by using a holistic design approach and dynamic building energy performance.	BPS	kindergarten	N/A	energy consumption	[59]
TI	2017	ja	Odense	Evaluating and improving the energy consumption of an office building.	BPS	two-storey office	1995	energy consumption	[60]
TI	2018	ja	Denmark	Studied the influence of thermal bridges in facade segments caused by interior insulation.	FEM analysis	multi-storey residential	1850–1930	energy consumption	[63]
TI	2018	c	Denmark	Simulating the dynamic performance of an office building, a preliminary assessment of the trade-off between deep energy retrofit and improving the building intelligence within an energy renovation process is provided.	BPS	single-storey office	1980s (renovated)	energy consumption	[61]
Direct/indirect gains									
DG/IG (ssp)	2000	c	Aalborg Vejle	Investigation of energy consumption of various glazed balcony designs.	BPS	multi-storey residential	1900 (renovated) 1950s (renovated)	energy consumption thermal comfort	[71]
DG/IG (sw)	2000	c	Kolding	Presentation and measurement of a solar wall.	Field study	two-storey residential	1998	temperature inside the storage	[34]
DG (w)	2014	ja	DRY	Providing a guide for designing well-insulated homes regarding window size, type and orientation, and their influence on energy consumption and thermal comfort.	BPS	single-family house	2015 2020	energy consumption thermal comfort	[69]
DG (w)	2015	ja	Copenhagen	Study the effect of size, orientation and physical glazing properties on space heating and indoor environmental quality.	BPS	single-family house	nearly zero-energy	energy consumption thermal comfort	[68]
DG (w)	2017	c	Aarhus/DRY	Simplification of the iterative design process to improve collaboration efficiency.	BPC/BPS	multi-storey office	-	energy consumption indoor environmental quality	[67]
DG (w)	2020	ja	Hvalsø	Methodology development for the optimisation of operational, embodied environmental and cost parameters in building renovations.	BPC/LCA/LCC	multi-storey residential	1969 (renovated)	energy consumption global warming potential costs	[70]

Table A1. *Cont.*

Passive Strategy	Publication Year	Publication Type	Project Location	Research Aim	Study Type	Building Type	Construction Year	Evaluation Criteria	Ref.
Solar shading									
SS	2011	ja	Denmark	Evaluation of the dynamic solar shading potential.	BPS	generic two-person office room	N/A (level 21st century)	energy consumption thermal comfort daylight	[77]
SS	2015	c	Aalborg	Development of dynamic facade system.	N/A	office building	N/A	energy consumption	[21]
SS	2016	ja	Copenhagen	Overheating assessment of renovation projects and evaluation of the effect of several renovation measures.	BPS	single-family house	1970–1980	thermal comfort	[74]
SS	2016	ja	Aalborg	Development of shading control strategy for Venetian blinds in offices.	BPS full-scale measurement	one-person office	N/A (level 21st century)	energy consumption vertical eye illuminance operative temperature	[76]
SS	2017	ja	Copenhagen	Comparison of dynamic solar shading to solar coated glazing in low-energy houses.	BPS	single-family house	low-energy	energy consumption thermal comfort daylighting	[75]
Natural ventilation									
NV	2007	ja	Copenhagen	Climatic potential evaluation for passive cooling in buildings by night-time ventilation in Europe.	calculation	-	-	climatic cooling potential	[91]
NV	2012	c	Copenhagen	Determine the most dominating driving forces for occupants opening and closing the window.	Field study	all kinds of dwellings	N/A	indoor environmental quality	[92]
NV	2012	c	Copenhagen	Comparison of three ventilation strategies.	BPS Field study	shopping centre	2004	thermal comfort energy consumption	[83]
NV	2014	ja	Vejle	Natural ventilation potential assessment for a passive house.	BPS	single-family house	passive house	energy consumption thermal comfort	[79]
NV, SS	2014	c	Hørsholm	Performance evaluation of kindergarten for light and thermal comfort.	Field study	kindergarten	2011	indoor environmental quality	[65]
NV, SS	2014	ja	Lystrup	Literature review of overheating risk, strategies to prevent overheating and measurement of active house.	Field study	single-family house	active house	indoor environmental quality	[54]
NV	2014	ja	Denmark	Presentation of data on the influence of different ventilation systems on classroom conditions.	Field study	school building	1970s	indoor environmental quality	[81]
NV	2015	c	Denmark	Comparison of occupants' perception, symptom prevalence and perceived control opportunities in buildings with a natural and mechanical ventilation system.	Statistical evaluation	office	N/A	occupant perception	[82]
NV	2016	c	Copenhagen	Potential of natural ventilation by window openings for the elimination of overheating.	BPS	single-family house	1970s (renovated)	thermal comfort	[80]
NV	2017	ja	Copenhagen	Estimation of natural ventilation potential of the world.	calculation	-	-	natural ventilation potential	[93]

Table A1. *Cont.*

Passive Strategy	Publication Year	Publication Type	Project Location	Research Aim	Study Type	Building Type	Construction Year	Evaluation Criteria	Ref.
				Radiative cooling					
RC	2015	c	Lyngby	Quantifying the cooling potential of PV/T panels and unglazed collectors during the night.	Measurement/BPS	-	-	cooling energy	[87]
RC	2016	c	Lyngby	Evaluation of the influence of different environmental parameters of PV/T panels.	BPS	-	-	energy consumption	[86]
RC	2016	c	Copenhagen	Analysing the potential of discharging PCM through night-time radiative cooling.	BPS	two-person office	-	energy consumption thermal comfort	[85]
RC	2019	c	Copenhagen	Estimation of the cooling potential of PV/T panels.	BPS	two-person office	-	energy consumption	[84]
				Evaporative cooling					
EC	2015	c	Denmark	Presentation of the technical potential of evaporative cooling systems.	calculation	office	-	energy consumption thermal comfort	[89]
EC	2020	c	Aarhus	Adiabatic cooling potential evaluation of using rainwater in public buildings.	Field study	school building	N/A	energy consumption thermal comfortwater consumption	[88]

c—conference, ja—journal article; DRY—Danish design reference year; BPS—Building Performance Simulation; BPC—Building Performance Calculation; LCA—Life cycle analysis; LCC—Life cycle cost; FEM—Finite element method; O—orientation, SZ—space zoning, BM—building massing, TM—thermal mass, TI—thermal insulation, DG—direct gain, IG—indirect gain, NV—natural ventilation, SS—solar shading, RC—radiative cooling, EC—evaporative cooling; w—window, ssp—sunspace, sw—solar wall.

Appendix B.2

Table A2. List of the 25 examined actual building projects concerning the application of passive design strategies in Denmark in the order of construction year.

Name	Location	Construction Year	Passive Cooling Strategy	Passive Heating Strategy	Building Type	Ref.
Farmhouse	Holmsland	1854	NV	O, SZ, BM	one-storey residential	[33]
The Yellow house	Aalborg	1900 (renovated)	-	DG/IG (ssp)	multi-storey residential	[71]
Østerbo	Vejle	1950s (renovated)	-	DG/IG (ssp)	multi-storey residential	[71]
Zoneopdelt	Greve	1985	-	DG (ssp), SZ, TM	one-storey residential	[36]
Aalborg Internationale Kollegium	Aalborg	1991	-	TI, IG (a), BM, O, ERC	two-storey residential	[38]
Andelssamfundet Hjortshøj	Hjortshøj	1993	-	TI, TM, SZ, DG (w)	two-storey residential	[38]
Solar Terraces	Vonsild	1994	-	TI, DG (w)	two-storey residential	[10]
Eco-house 99	Kolding	1998	-	O, DG (w, sw), TM	two-storey residential	[34]
Den Kompakte Bebyggelse	Skejby	1998	NV	TI, DG (w), O	two-storey residential	[36]
Bogholder Allé	Vanløse	2003	-	TM, DG (w)	multi-storey residential	[10]
Danish Broadcasting Media House	Copenhagen	2006	NV	DG (w)	multi-storey office	[72]
Home for Life	Lystrup	2009	SS, NV	DG (w), TI, TM	single-family house	[53,54]

Table A2. *Cont.*

Name	Location	Construction Year	Passive Cooling Strategy	Passive Heating Strategy	Building Type	Ref.
Energy Flex House	Taastrup	2009	DG (reduced w. area), SS, NV, TM	TM	single-family house	[53]
Comfort Houses	Vejle	2009	-	TI, DG (w)	single-family house	[10,66]
Rambøll Head Office	Copenhagen	2010	SS	O, TI	multi-storey office	[35]
Viborg City Hall	Viborg	2011	EC (vegetation), NV	-	public building	[39]
Solhuset	Hørsholm	2011	NV, SS	TI, DG (w)	kindergarten	[65,73]
World Flex house	Frederiksværk	2012	-	O, TI, DG (w)	single-family house	[37]
Hal C	Copenhagen	2013	NV, SS	-	sport facility	[78]
The Modern Seaweed House	Laesø	2013	NV	TI, DG (w)	single-family house	[37]
Novo Nordisk Corporate	Bagsværd	2013	EC (vegetation)	BM, DG (a), SZ (buffer)	multi-storey office	[39]
University of Southern Denmark	Kolding	2014	NV, SS	DG/IG (a), SZ, TM	educational building	[39]
Lego Campus in Billund	Billund	2019	SS, EC (vegetation)	DG (w), TI, BM	multi-storey office	[42]
The Resource Rows	Ørestad	2019	NV, SS	TM, DG (w)	multi-storey residential	[55]
Solbjerg school	Aarhus	-	EC with rainwater	-	one-storey school	[88]

O—orientation, SZ—space zoning, BM—building massing, TM—thermal mass, TI—thermal insulation, DG—direct gain, IG—indirect gain, NV—natural ventilation, SS—solar shading, EC—evaporative cooling, ERC—earth coupling; w—window/glazing, ssp—sunspace, sw—solar wall, a—atrium.

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